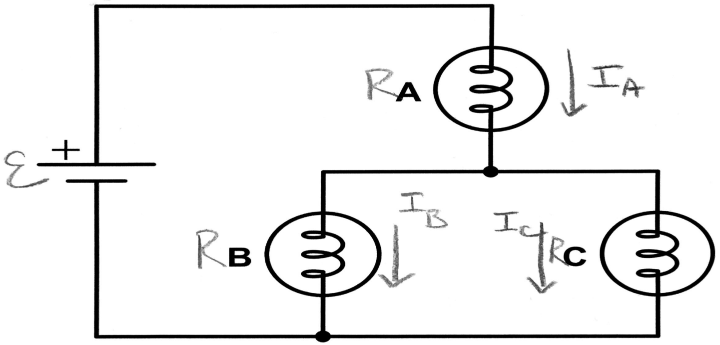
Physics 9 — Wednesday, December 5, 2018

- "Practice exam" (due on the last day of class, 12/10) is effectively a take-home portion of your final exam, intended to help you to prepare for the in-class exam (12/17).
- HW11 due this Friday. (Last one!)
- For today, you read Eric Mazur's ch 27 (magnetic interactions), which will help us to see how to make electricity do useful work (turn a motor, ring a doorbell, etc.)
- FYI: positron.hep.upenn.edu/wja/p009/2016/files/exam.pdf positron.hep.upenn.edu/wja/p009/2016/files/exam_solns.pdf
- Full-featured python interpreter in a web browser: https://www.pythonanywhere.com/try-ipython/
- HW help sessions: Wed 4–6pm DRL **4C2** (Bill), Thu 6:30–8:30pm DRL 2C8 (Grace)
- If you want to "build" some circuits on your (or your neighbor's) computer in class today:

https://phet.colorado.edu/en/simulation/circuit-construction-kit-dc

- Since 14 of you did the (optional/XC) Arduino reading, does anyone want to work in small groups with Arduinos and breadboards for a couple of hours during Reading Days?
- `https://doodle.com/poll/hwf78raekkknb2ey`
- Other XC options: read/summarize Muller PTFP chapters:
  - 04 – nuclei and radioactivity
  - 05 – chain reactions, nuclear reactors, and atomic bombs
  - 11 – quantum physics
  - 12 – relativity
  - 13 – the universe
  - `muller_effp_ch3.pdf` is a slightly more up-to-date (2012) chapter by Muller on Climate Change
- Or you can read/summarize one or more chapters from an Architectural Acoustics book by Egan (`egan_ch1.pdf` etc.)
- Or read/summarize 3 Eric Mazur chapters giving a more mathematical look at entropy & thermodynamics.
- Giancoli's chapter on astronomy (or others if you like)
- Or read+do tutorials on Mathematica for math calculations
- Or code in Processing (java or python): see my Nov 21 slides



After solving 3 eqns for 3 unknowns:

Junction rule:

$$I_A = I_B + I_C$$

Loop rule:

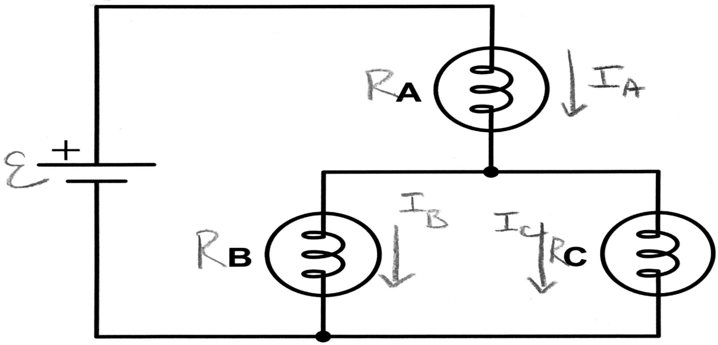
$$\mathcal{E} - I_A R_A - I_B R_B = 0$$

$$\mathcal{E} - I_A R_A - I_C R_C = 0$$

$$I_A = \frac{\mathcal{E}}{R_A + \left(\frac{R_B R_C}{R_B + R_C}\right)}$$

$$I_B = \left(\frac{R_C}{R_B + R_C}\right) I_A$$

$$I_C = \left(\frac{R_B}{R_B + R_C}\right) I_A$$



$$I_A = \frac{\mathcal{E}}{R_A + \left(\frac{R_B R_C}{R_B + R_C}\right)}$$

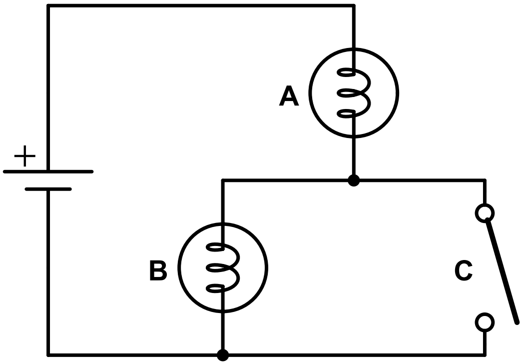
$$I_B = \left(\frac{R_C}{R_B + R_C}\right) I_A$$

$$I_C = \left(\frac{R_B}{R_B + R_C}\right) I_A$$

If $R_A = R_B = R_C = R \neq 0$ then

$$I_A = \frac{\mathcal{E}}{R + \frac{1}{2}R} = \frac{\mathcal{E}}{\frac{3}{2}R} = \frac{2\mathcal{E}}{3R}$$

$$I_B = I_C = \left(\frac{1}{2}\right) I_A = \frac{\mathcal{E}}{3R}$$



$$I_A = \frac{\mathcal{E}}{R_A + \left(\frac{R_B R_C}{R_B + R_C}\right)}$$

$$I_B = \left(\frac{R_C}{R_B + R_C}\right) I_A$$

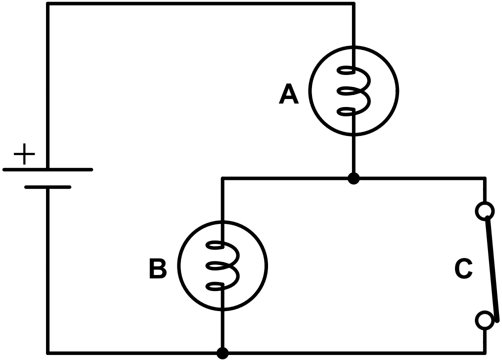
$$I_C = \left(\frac{R_B}{R_B + R_C}\right) I_A$$

If $R_A = R_B = R \neq 0$ and $R_C = \infty$ then

$$I_A = \frac{\mathcal{E}}{R + R} = \frac{\mathcal{E}}{2R}$$

$$I_B = I_A = \frac{\mathcal{E}}{2R}$$

$$I_C = 0$$



$$I_A = \frac{\mathcal{E}}{R_A + \left(\frac{R_B R_C}{R_B + R_C}\right)}$$

$$I_B = \left(\frac{R_C}{R_B + R_C}\right) I_A$$

$$I_C = \left(\frac{R_B}{R_B + R_C}\right) I_A$$

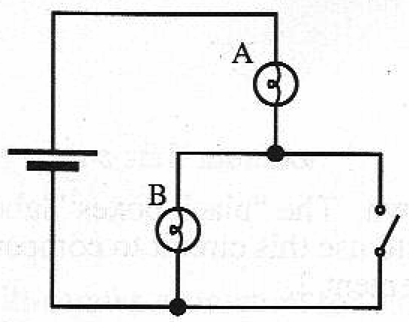
If $R_A = R_B = R \neq 0$ and $R_C = 0$ then

$$I_A = \frac{\mathcal{E}}{R + 0} = \frac{\mathcal{E}}{R}$$

$$I_C = I_A = \frac{\mathcal{E}}{R}$$

$$I_B = 0$$

If you were to build this circuit, when would bulb A be brighter?

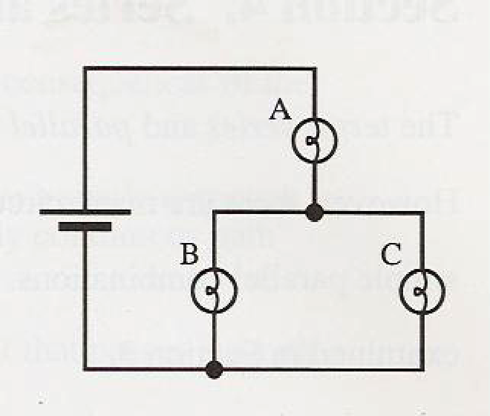


(A) A is brighter when the switch is open

(B) A is brighter when the switch is closed

(C) A is the same brightness in both cases

Predict the relative brightness for the three bulbs (assuming the bulbs are identical). Once you predict, feel free to try it — either by combining parts with two other groups or by using the "circuit construction kit: DC" web app!



(A) $A < B < C$

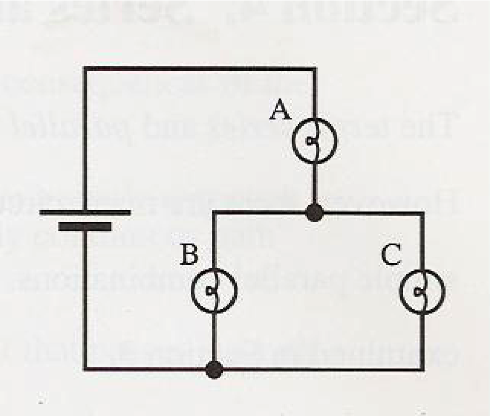
(B) $A < B = C$

(C) $A = B = C$

(D) $A > B = C$

(E) $A > B > C$

You just predicted $A > B = C$ when all 3 (identical) bulbs are present. Now predict what will happen to the brightness of bulbs A and B if bulb C is unscrewed. Once you predict, feel free to try it.



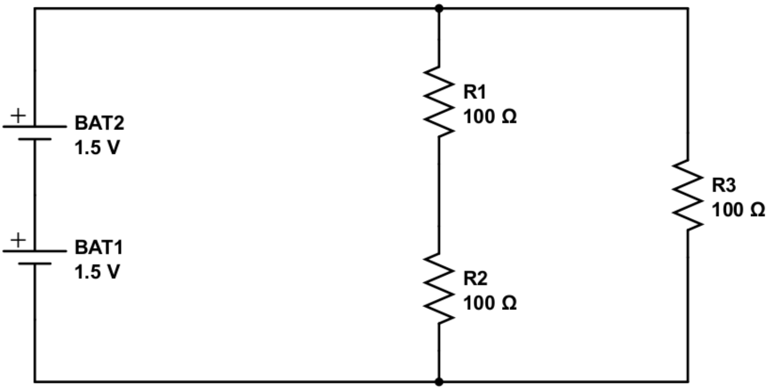
(A) A and B will both become brighter.

(B) A and B will both become dimmer.

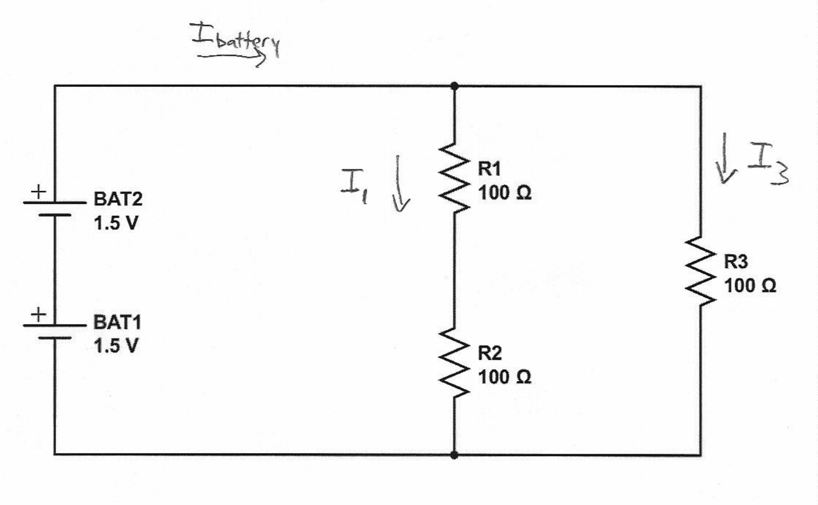
(C) A will become brighter, and B will become dimmer.

(D) A will become dimmer, and B will become brighter.

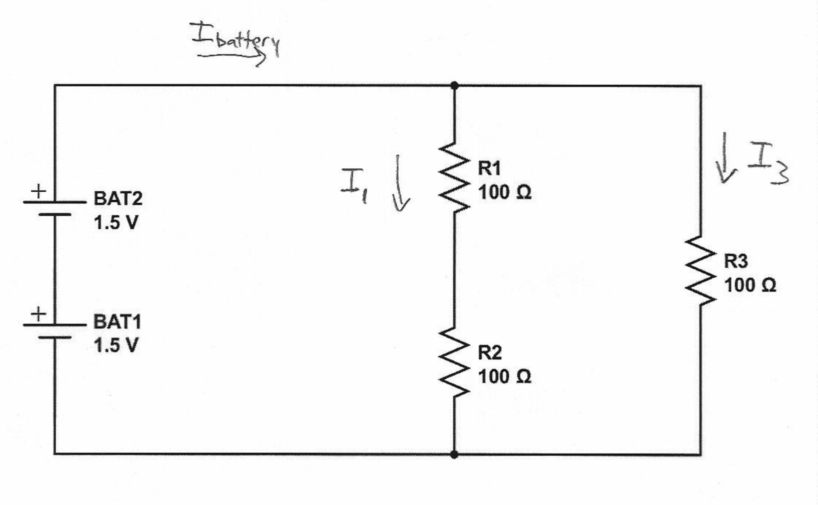
(E) The brightness of A and B will not change.



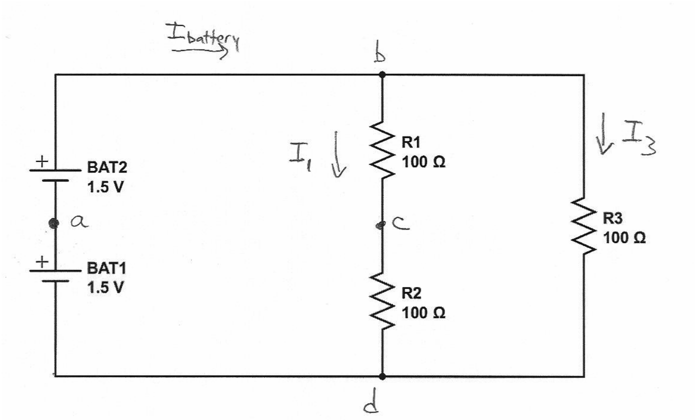
First, identify all of the **branches** in the circuit. For each branch, choose a **reference direction** for the current through that branch. How many branches? How many junctions?



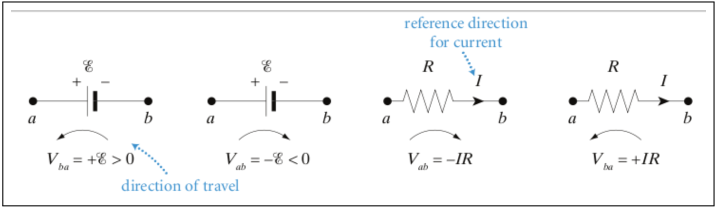
What does the **junction rule** let us write for the junction above R_1? In this case, do we get any additional information by applying the junction rule at the junction below R_2?

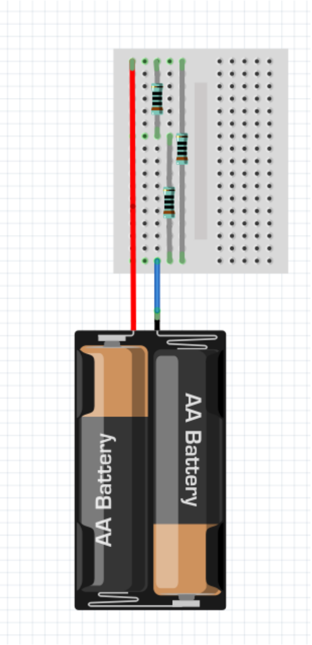


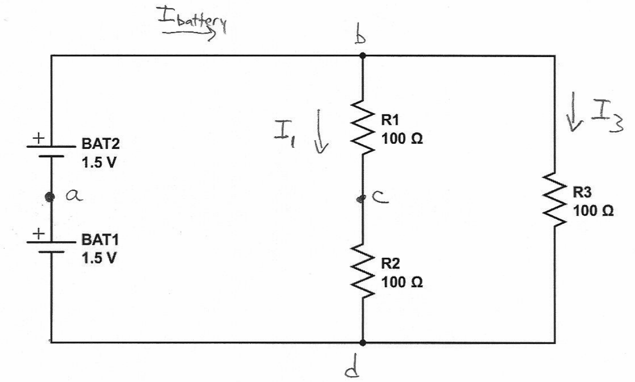
There are 3 loops in this circuit. Where are they? Use the loop rule for each one. (Let's go clockwise around each loop — arbitrary choice.) How many of these 3 equations give us new information?



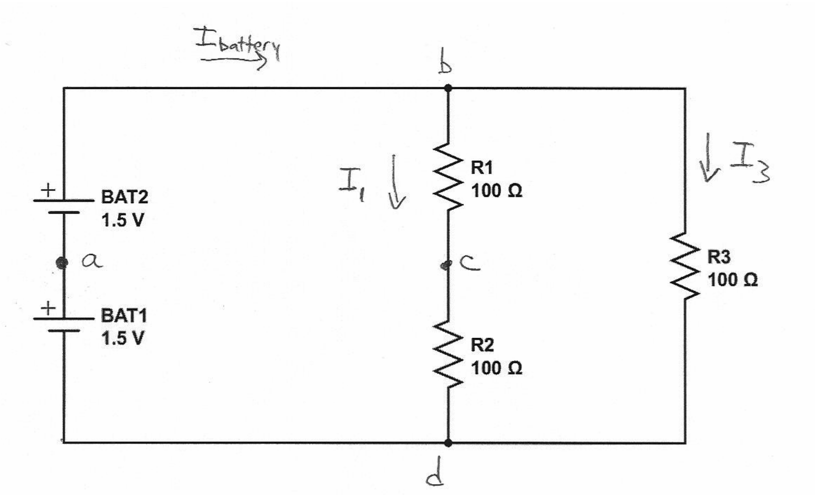
Now predict V_{ab}, V_{bc}, V_{cd}, V_{bd}, and V_{da}.





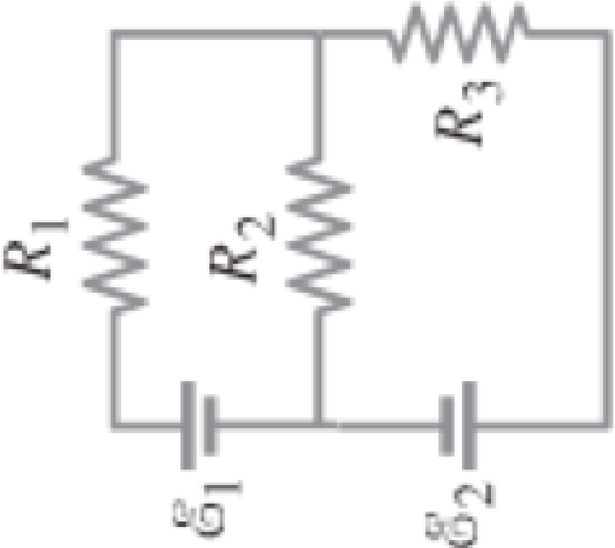


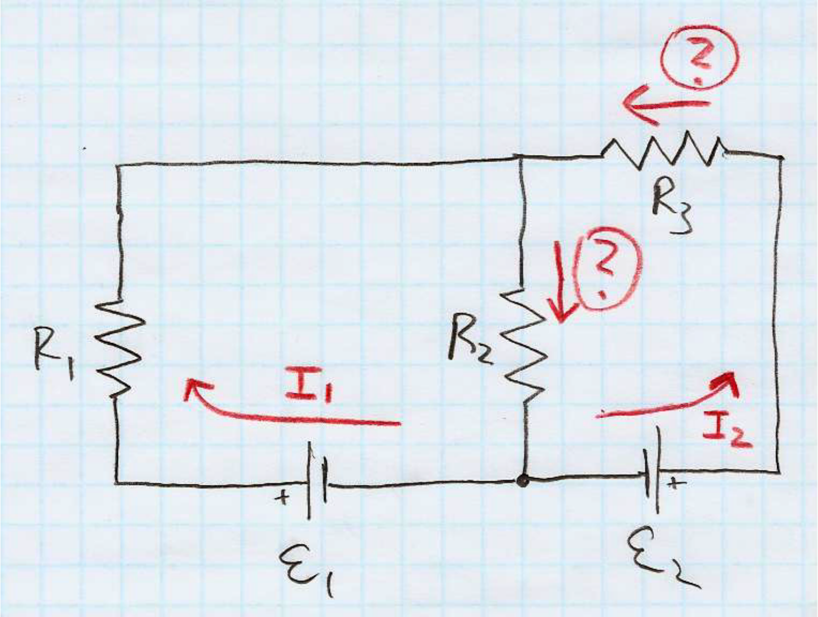
see fritzing.org to draw left, circuitlab.com for right



One more question: What is the power dissipated in each resistor? (Are they all the same, or not?) What is the power supplied by each battery?

Circuits with multiple batteries can be tricky: particularly for getting the signs right. When feasible, I usually try to draw a current going "the conventional way" through each battery, e.g. I_1 going to the left through $\mathcal{E}_1$ and I_2 going to the right through $\mathcal{E}_2$.





What values can we write for the two **?** currents?

What does the loop rule tell us? (3 equations, but 1 is redundant.)

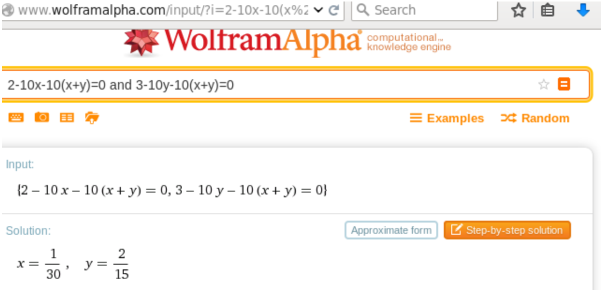
For example, let's plug in
$R_1 = R_2 = R_3 = 10\ \Omega,\quad \mathcal{E}_1 = 2\ \mathrm{V},\ \mathcal{E}_2 = 3\ \mathrm{V}$. Then we get

$$2\ \mathrm{V} - (10\ \Omega)I_1 - (10\ \Omega)(I_1 + I_2) = 0$$

$$3\ \mathrm{V} - (10\ \Omega)I_2 - (10\ \Omega)(I_1 + I_2) = 0$$

If you have two equations in two unknowns (e.g. x and y), you can go to Wolfram Alpha and type (for example)

`2-10x-10(x+y)=0 and 3-10y-10(x+y)=0`



For example, let's plug in
$R_1 = R_2 = R_3 = 10\ \Omega$, $\mathcal{E}_1 = 2$ V, $\mathcal{E}_2 = 3$ V. Then we get

$$2\text{ V} - (10\ \Omega)I_1 - (10\ \Omega)(I_1 + I_2) = 0$$

$$3\text{ V} - (10\ \Omega)I_2 - (10\ \Omega)(I_1 + I_2) = 0$$

Or you can use Mathematica . . .

```
In[9]:= ClearAll["Global`*"];
        Reduce[{
          2 - 10 I1 - 10 (I1 + I2) == 0,
          3 - 10 I2 - 10 (I1 + I2) == 0
         }]
```

Out[10]= $I2 == \frac{2}{15}$ && $I1 == \frac{1}{30}$

For example, let's plug in

$R_1 = R_2 = R_3 = 10\ \Omega, \quad \mathcal{E}_1 = 2\ \mathrm{V},\ \mathcal{E}_2 = 3\ \mathrm{V}$. Then we get

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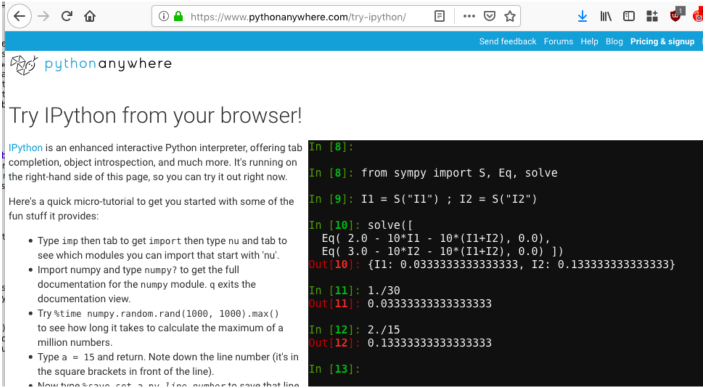
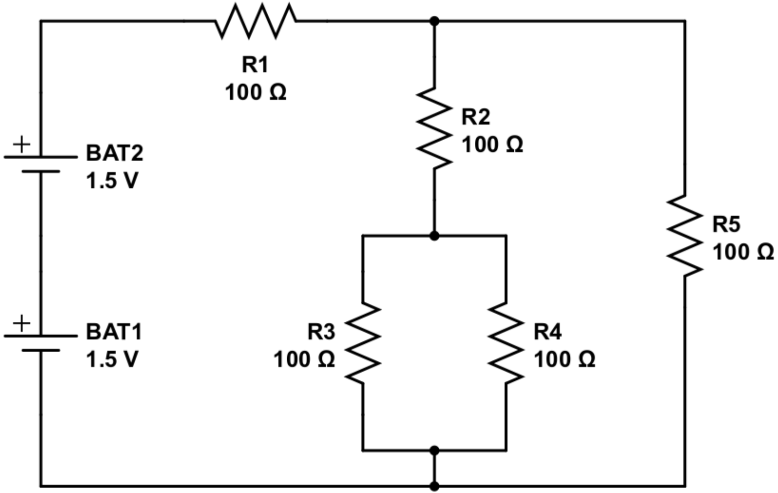
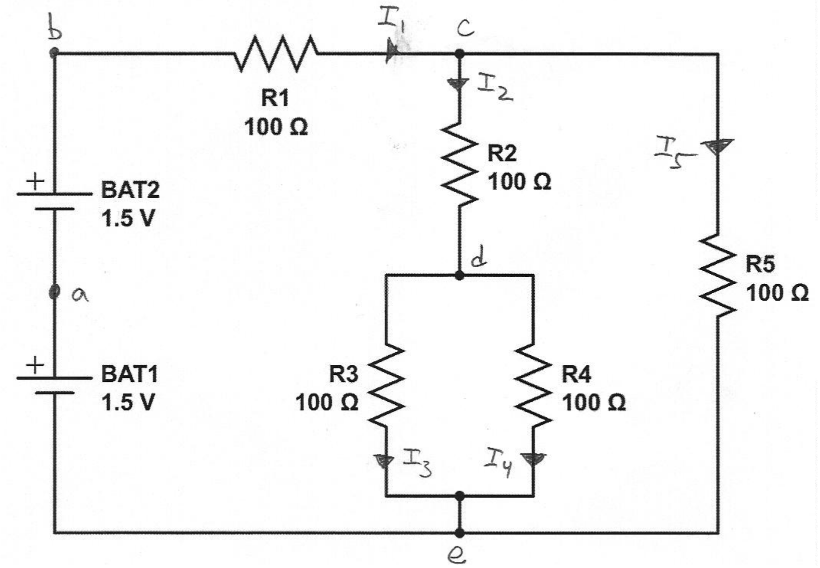
$$3\ \mathrm{V} - (10\ \Omega)I_2 - (10\ \Omega)(I_1 + I_2) = 0$$

Or you can use "Sympy" in Python ...

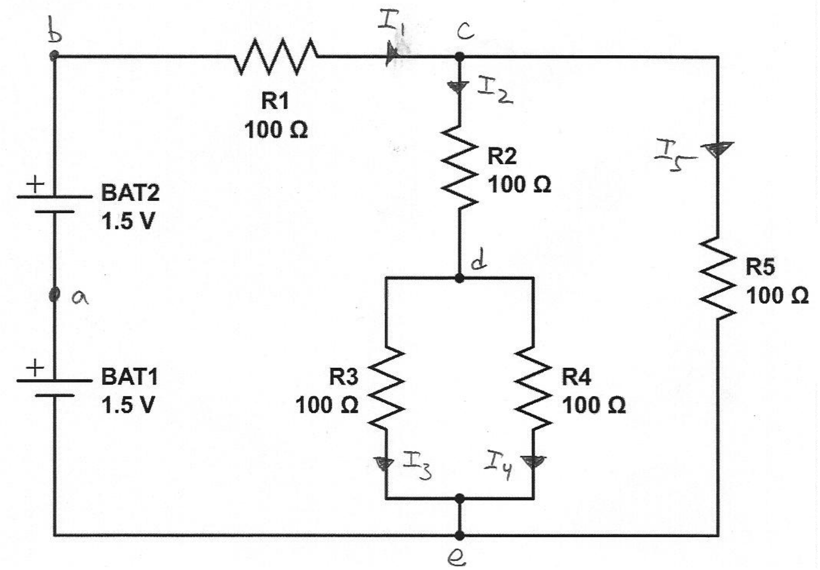




This circuit is more complicated. How many branches? Let's choose a reference direction for each branch, choose a name for the current in each branch, and choose a name for all points between which we might want to measure voltage. (Next page.)



What does junction rule let us write at point *c*? Point *d*? Does the junction rule at point *e* tell us anything new?



I count 4 loops. Let's see what the loop rule tells us. Again, one equation will be redundant. We'll just write down the equations, without wasting time to solve them for $I_1 \ldots I_5$.

loop rule:

$$\mathcal{E}_1 + \mathcal{E}_2 - I_1 R_1 - I_5 R_5 = 0$$

$$\mathcal{E}_1 + \mathcal{E}_2 - I_1 R_1 - I_2 R_2 - I_3 R_3 = 0$$

$$\mathcal{E}_1 + \mathcal{E}_2 - I_1 R_1 - I_2 R_2 - I_4 R_4 = 0$$

junction rule:

$$I_1 = I_2 + I_5 \Rightarrow \boxed{I_5} = I_1 - I_2$$

$$I_2 = I_3 + I_4 \Rightarrow \boxed{I_4} = I_2 - I_3$$

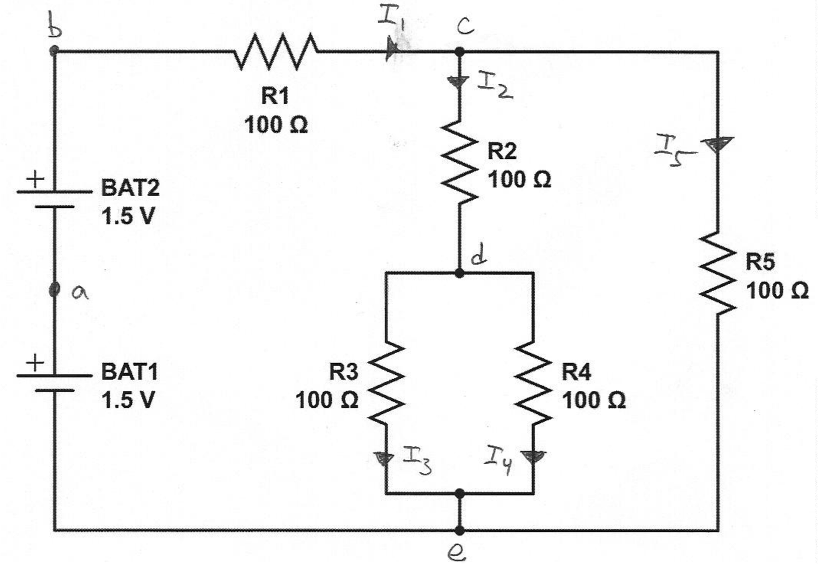
Plug these in to eliminate I_4, I_5:

$$\mathcal{E}_1 + \mathcal{E}_2 - I_1 R_1 - (I_1 - I_2) R_5 = 0$$

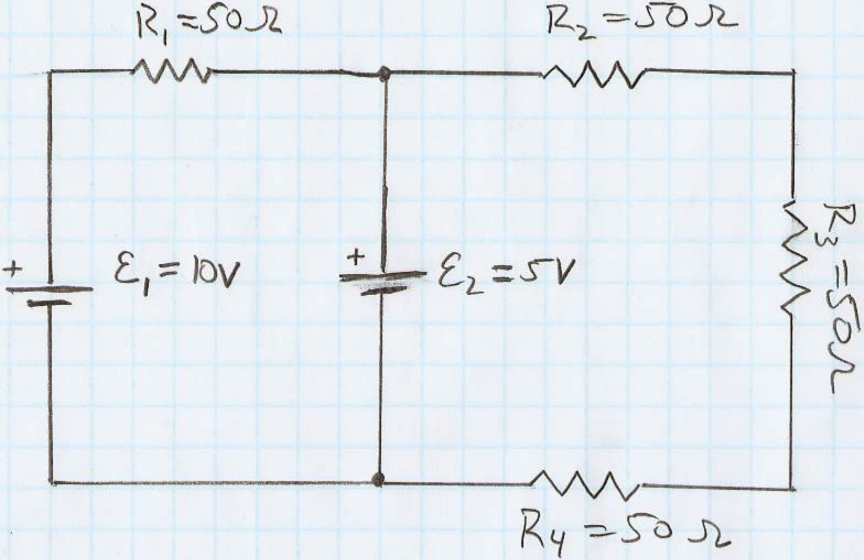
$$\mathcal{E}_1 + \mathcal{E}_2 - I_1 R_1 - I_2 R_2 - I_3 R_3 = 0$$

$$\mathcal{E}_1 + \mathcal{E}_2 - I_1 R_1 - I_2 R_2 - (I_2 - I_3) R_4 = 0$$

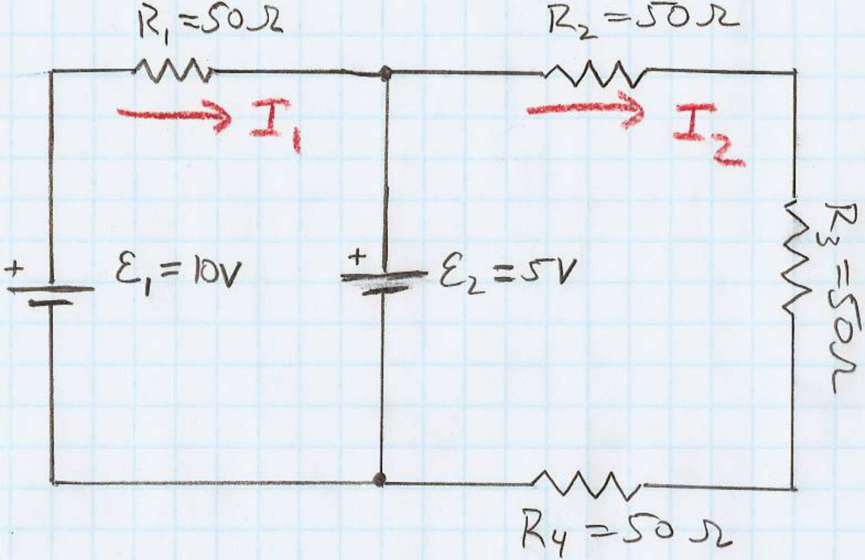
(Notice that $I_3 R_3 - I_4 R_4 = 0$ is same as we would get by subtracting the last 2 eqns.)



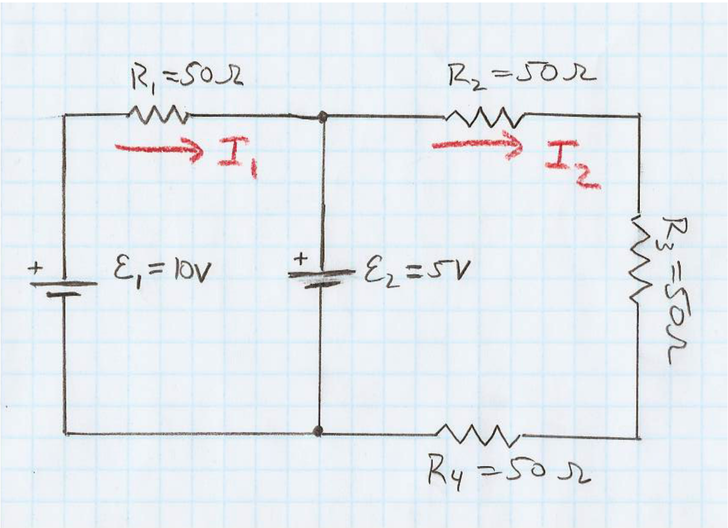
$$I_1 = 0.01875\,\mathrm{A},\ I_2 = 0.0075\,\mathrm{A},\ I_3 = I_4 = 0.00375\,\mathrm{A},\ I_5 = 0.01125\,\mathrm{A}$$
$$I_1R_1 = 1.875\,\mathrm{V},\ I_2R_2 = 0.75\,\mathrm{V},\ I_3R_3 = I_4R_4 = 0.375\,\mathrm{V},\ I_5R_5 = 1.125\,\mathrm{V}$$



R1 = 50 Ω
R2 = 50 Ω
R3 = 50 Ω
R4 = 50 Ω
ε1 = 10V
ε2 = 5V
+
+



R1 = 50 Ω
R2 = 50 Ω
I1
I2
+
ε1 = 10V
+
ε2 = 5V
R3 = 50 Ω
R4 = 50 Ω



8. In the left figure below, the first battery emf (i.e. its "voltage") is $\mathcal{E}_1 = 10$ V and the second battery emf is $\mathcal{E}_2 = 5V$. All resistors are 50 Ω. (a) Find the current through and the potential difference across each resistor. (b) What is the power dissipated in each resistor? (c) What is the power supplied by (or perhaps consumed by?) each battery? Don't forget to check that the sum of your answers for part b agrees with the sum of your answers for part c.

Wall outlets in a building supply **alternating current** (AC), whereas a battery supplies *direct current* (DC). My animation:

https://youtu.be/0wgoPM13kIs

Convention: black=hot, white=neutral, green/bare=ground.

$$V(t) \;=\; V_{\rm max} \sin(2\pi f t)$$

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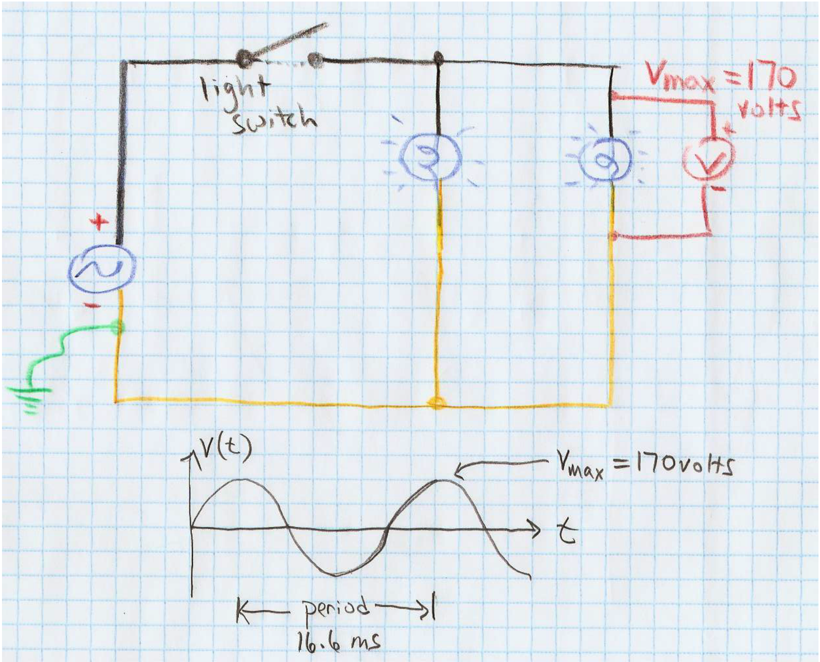
Convention: black=hot, white=neutral, green/bare=ground.

$$V(t) \;=\; V_{\max} \sin(2\pi f t)$$

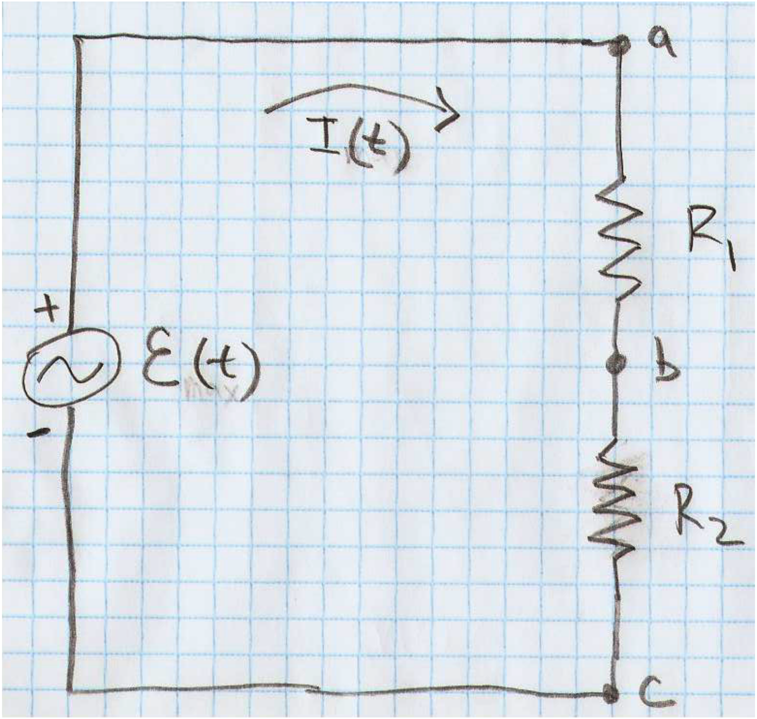
$V_{\max} = 170$ volts, $f = 60$ hertz.

$$V_{\mathrm{rms}} \;=\; \sqrt{\;\overline{V^2(t)}\;} \;=\; 120 \text{ volts}$$

(Remember that $\overline{\sin^2(\theta)} = \frac{1}{2}$ so $V_{\mathrm{rms}} = V_{\max}/\sqrt{2}$.)

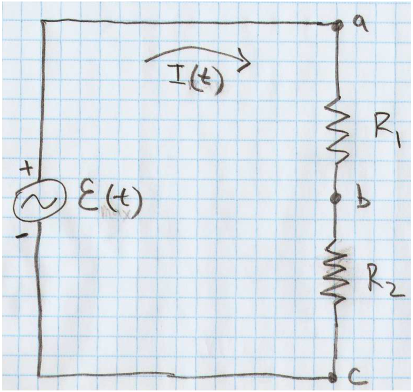


light switch
Vmax = 170 volts
+
-
V(t)
Vmax = 170volts
t
period
16.6 ms



a
I(t)
R1
+
E(t)
-
b
R2
c

The usual "junction rule" and "loop rule" work for AC too, but voltage and current are functions of time now.



In series, each resistor (or light bulb) gets only a fraction of the total emf. So light fixtures are always in parallel, not in series (except holiday lights, etc.).

$$\mathcal{E}(t) - I(t)R_1 - I(t)R_2 = 0$$

Solving for current, we get

$$I(t) = \frac{\mathcal{E}(t)}{R_1 + R_2}$$

Voltage across top resistor is

$$V_{ba}(t) = I(t)R_1 = \frac{R_1}{R_1 + R_2}\mathcal{E}(t)$$

V across bottom resistor is

$$V_{cb}(t) = I(t)R_2 = \frac{R_2}{R_1 + R_2}\mathcal{E}(t)$$

If I plug a 60 watt light bulb into a standard household light fixture, what is the r.m.s. (root mean square) current that flows through the bulb?

(A) 2.8 amps

(B) 2.0 amps

(C) 1.0 amp

(D) 0.83 amp

(E) 0.5 amp

If I use several “power strips” and several outlets to try to operate 100 separate 60-watt lamps simultaneously from the same (120 volt r.m.s.) household circuit, how much current (r.m.s.) flows through the fuse or circuit breaker that protects this circuit?

(A) 0.5 amp

(B) 5 amps

(C) 50 amps

What is the r.m.s. current drawn by an 1800-watt hair dryer, operating from a standard 120-volt (r.m.s.) household outlet?

(A) 1.5 amps

(B) 10 amps

(C) 15 amps

(D) 25 amps

A typical U.S. house uses about 1000 kWh per month, i.e. on average about 1400 watts, or about 12 amps (at 120 V).

This varies a lot with season and time of day. So a typical U.S. house has 200-amp service coming in from the street, i.e. capable of 24000 watts, in case you have electric stove, electric water heater, clothes dryer, A/C, hair dryer, etc., all running at once.

Imagine that 500,000 homes in Philadelphia are using 20 amps (r.m.s.) each one evening. That's 1.2 gigawatts, which is about what a typical gas/coal/nuclear power plant generates.

At 120 volts, the total current from the power station to the city would be 10^7 amps.

In a copper wire of 1 cm radius, the voltage drop after just 2 kilometers ($R \approx 0.1\ \Omega$) would be $IR \approx 10^6\ \mathrm{V}$.

What if the power were instead transmitted at a much higher voltage, like 100 kV ?

Copper wire: 1 cm radius, 2 km length would have $R \approx 0.1\ \Omega$. We want to send 10^9 watts to Philadelphia. What if the power were transmitted at 100 kV instead of 120 V ?

Need "only" 10,000 amps: $(100\ \mathrm{kV})(10\ \mathrm{kA}) = 1\ \mathrm{GW}$.

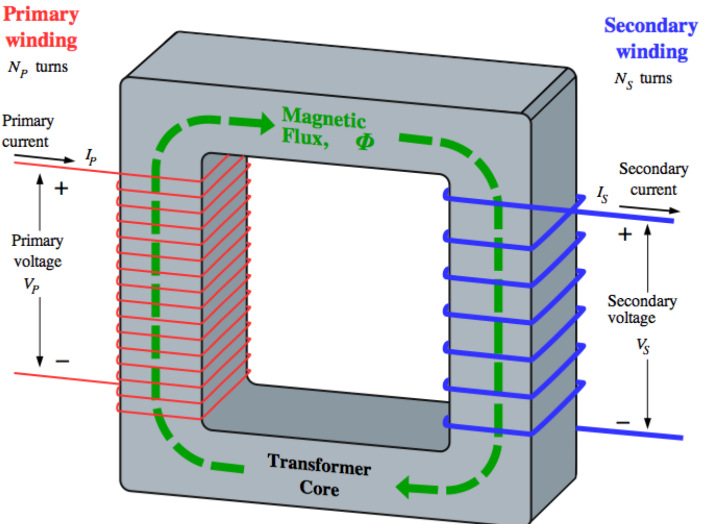
Voltage drop on 2 km copper wire is then $IR = 1\ \mathrm{kV}$, which is only 1% of the voltage put out by the power plant. So only 1% of the plant's power is wasted in heating up the transmission line.

Power delivered is IV — that's current times voltage. The power wasted in heating up the cable is $I^2 R_{\mathrm{cable}}$. So to deliver high power over long distances, we want to keep I as small as possible while keeping the product IV large. So very high voltages are used for long-distance power distribution.

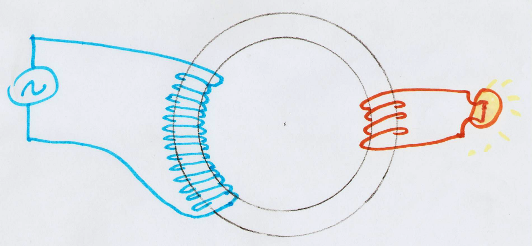
How can you convert from (high current) $\times$ (low voltage) into (low current) $\times$ (high voltage) and back? A transformer!

Transformer: it only works with AC, not DC!

$$\mathcal{E}_S = N_S \frac{\mathrm{d}\Phi_B}{\mathrm{d}t}, \qquad \mathcal{E}_P = N_P \frac{\mathrm{d}\Phi_B}{\mathrm{d}t} \qquad \Rightarrow \qquad \frac{\mathcal{E}_S}{\mathcal{E}_P} = \frac{N_S}{N_P}$$

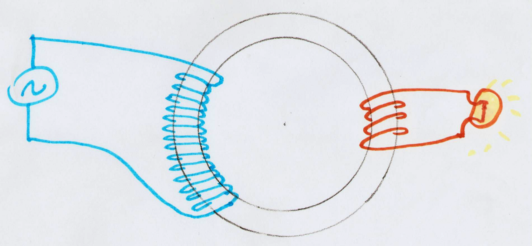


Consider an ideal step-down transformer in which the primary coil has 1000 turns and the secondary coil has 100 turns. The primary is connected to an AC power source, and the secondary is connected to a light bulb. If the rms voltage delivered by the AC power source is 120 volts, what is the rms voltage across the bulb?



(A) 1.2 volts
(B) 12 volts
(C) 120 volts
(D) 1200 volts

Consider an ideal step-down transformer in which the primary coil has 1000 turns and the secondary coil has 100 turns. The primary is connected to an AC power source, and the secondary is connected to a light bulb. If the rms current delivered by the AC power source is 0.1 amp, what is the rms current through the bulb?



(A) 0.01 amp
(B) 0.1 amp
(C) 1.0 amp
(D) 10 amps

Hint: the **power** on each side of an ideal transformer is the same. $P = IV$.

Other demos:

- Household light switch with bulb & battery
- Three-way stairway light switch
- Magnets & electromagnet & doorbell & speaker
- Motor & generator

Physics 9 — Wednesday, December 5, 2018

- “Practice exam” (due on the last day of class, 12/10) is effectively a take-home portion of your final exam, intended to help you to prepare for the in-class exam (12/17).
- HW11 due this Friday. (Last one!)
- For today, you read Eric Mazur’s ch 27 (magnetic interactions), which will help us to see how to make electricity do useful work (turn a motor, ring a doorbell, etc.)
- FYI: positron.hep.upenn.edu/wja/p009/2016/files/exam.pdf
  positron.hep.upenn.edu/wja/p009/2016/files/exam_solns.pdf
- Full-featured python interpreter in a web browser:
  https://www.pythonanywhere.com/try-ipython/
- HW help sessions: Wed 4–6pm DRL **4C2** (Bill),
  Thu 6:30–8:30pm DRL 2C8 (Grace)
- If you want to “build” some circuits on your (or your neighbor’s) computer in class today:

https://phet.colorado.edu/en/simulation/circuit-construction-kit-dc